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Simultaneous Wireless Information and Power Transfer Over K_G Fading Channels

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Abstract: In this paper, we proposed a novel expression for the probability density function (PDF) and the cumulative density function (CDF) of the output SNR for the M-branch Selection Combining (M-SC) receiver over Generalized-K (K_G) fading channels. Unlike conventional energy sources, the proposed scheme uses a Power splitter (PS) scheme at the receiver side. The received signal is split into information decoding and energy harvesting receiver with adjustable power levels. The expressions of our system consider arbitrary channel parameters and diversity branches. We analyze the proposed model and derive the closed-form expression for average SNR and average bit error rate (ABER) to evaluate the system performance. The obtained results are corroborated with the help of Monte-Carlo simulations. The effects of system parameters, such as power splitter ratio, modulation order, and shaping parameters of K_G fading channels, are studied. This type of system will benefit reliable data transmission in an energy-limited scenario.

Keywords: Generalized-*K* fading, diversity, selection combining, power splitter, average SNR, ABER.

1. Introduction

In wireless communication receivers, the main objective is to diminish the effect of fading as much as possible. Accurate modelling of wireless channels significantly helps the design engineer to reduce this effect. Generalized-K (K_G) combines Nakagami-m and Gamma distribution which accurately approximates Nakagami-lognormal distribution [1]. The particular case of *K*-distribution results in the K_G fading model, and it also amalgamates the fading/shadowing phenomena in wireless communication channels. The Generalized-*K* distribution makes the mathematical expression much more straightforward, and it is closely correlated to Nakagami-m or the Rayleigh lognormal model.

The diversity technique improves the received signal quality and exploits the lower probability of deep fades depend on the various fading paths. Depending upon the combining approaches, the diversity receiver's performance and complexity vary. In our proposed model, selection combining is considered for its simpler implementation and is frequently used in practice [2]. The SC diversity receiver is more suitable due to low complexity and low power consumption in modern wireless technology applications like cognitive radio (CR) and wireless sensor networks (WSN) systems in providing reliable quality of service in severe environments for degrading effects of fading. As mentioned above, this fading channel has drawn the full attention of researchers for almost a decade [3–5]. In [3] and [4], the author considered multi-hop links between source and destination, and the performance of MRC receiver over K_G fading channels has been studied, respectively. Further, the performance analysis of the SC receiver in the K_G fading channels using MGF based approach has been presented in [5]. The outage of an SC receiver for *K* fading channels using exponential correlation has been studied for a correlation coefficient less than 0.5 in [6].

In recent years, energy harvesting (EH) has been considered an innovative idea to extend the lifetime battery of wireless sensor networks [7]. Replacing or recharging batteries can sustain a high cost and can be inconvenient or

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unpredictable (e.g., in harsh environments) [8, 9]. For this purpose, energy harvesting provides a safe and favorable option for charging wireless devices. Among the various conventional methods, the radio frequency (RF) signals have obtained significant attention for wireless power transfer (WPT) [10]. RF signals can convey both information and energy simultaneously, which gives a new and interesting research study. This unified study is termed as simultaneous wireless information and power transfer (SWIPT). For this purpose, the concept of simultaneous wireless information and power transfer is introduced and quickly became a significant research area in both industry and academic fields. Further, this technique simplifies the complexity of the wireless networks and reduce the expense of recharging and replacing batteries. However, energy harvesting with SWIPT has been presented, where two advanced protocols are used, such as Power splitting (PS) and Time switching (TS) in [11]. In most of the works, the performance analysis for WPT systems was presented in [11, 12]. In [12], the author has analyzed the performance parameters, such as outage probability and the average error rate of a wireless powered system for Nakagami-m fading using the TS technique. The impact of storing energy for the wirelessly powered technique has been studied in [13]. In [14], the article gives an overview of SWIPT that simultaneously enables information and energy transmission, providing energy and spectral efficiency considering 5G and beyond 5G wireless networks. In [15], the author investigates space shift keying modulation with SWIPT based on AF relay over Nakagami fading channel to analyze the system performance. To the best of our knowledge, researchers have not analyzed the power splitters scheme for SWIPT systems without any diversity techniques. These motivate us to incorporate the effect of fading parameters and the power splitter factor to represent the realistic fading environment. In this work, we have presented the closed-form expressions for the PDF and CDF of the output SNR employing an M-SC receiver in K_G fading environment, considering a power splitter ratio at the receiver side to achieve average SNR and ABER for various modulation schemes. However, the effect of fading parameters on the performance analysis has been verified through simulation results. Further, we also study the impact of harvested power at the receiver on the performance of SC diversity schemes.

This paper has been organized as per the following sections. Section 2 presents the system model of the K_G fading channel. Performance analysis of the SC receiver has been described in Section 3. The numerical results are discussed in Section 4, and at last we conclude the paper.

2. Generalized-*K* Fading Model

The Generalized-K fading channel is considered to be slow and frequency non-selective. We consider the proposed model for evaluation of the system performance in Fig. 1.

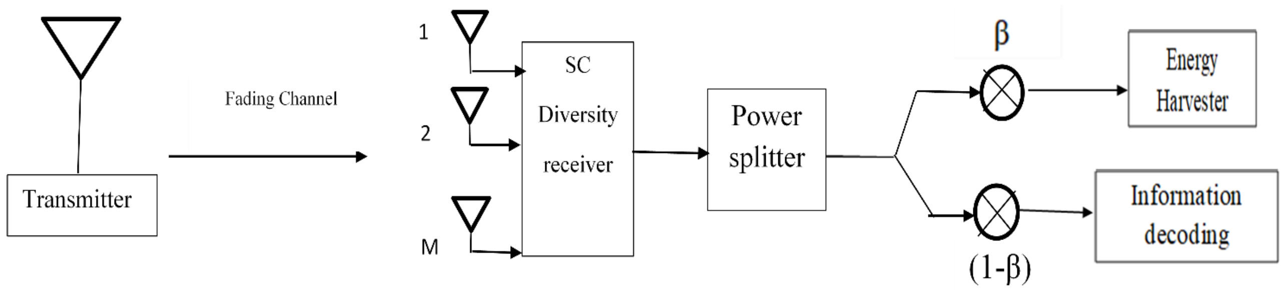

Fig. 1 - The proposed model

Assuming the fading channel with additive white Gaussian noise (AWGN), the signal received by the antenna with r = 1, 2, M of the diversity receiver can be expressed as

$$s_r(t) = y_r e^{j\psi_r(t)} z(t) + n_r(t), \tag{1}$$

Where, z(t) is the transmitted signal with energy per bit E_b and $n_r(t)$ is the complex Gaussian noise with zero mean and two-sided power spectral density $2N_0$. The noise components are independent and uncorrelated from each other. Random variable (RV) ψ_r denotes the phase and y_r represents the fading amplitude of K_G distribution having PDF taken from [1]

$$p_Y\left(y_r\right)=\frac{4y_r^{m+k-1}}{\Gamma\left(m\right)\Gamma\left(k\right)}\left(\frac{m}{\Omega}\right)^{\frac{k+m}{2}}\mathrm{K}_{k-m}\left[2\left(\frac{m}{\Omega}\right)^{\frac{1}{2}}y_r\right],\qquad y_r\geq 0 \tag{2}$$

where, k and m are the two shaping parameters. $K_{k-m}\left(\cdot\right)$ is the modified Bessel function of order $\left(k-m\right)$, $\Gamma(\cdot)$ is the incomplete Gamma function. Further, Ω is the mean power defined as $\Omega=E\left\langle Y^2\right\rangle/k$, with $E\left\langle\cdot\right\rangle$ denotes expectation.

The SC receiver selects the best signal among the M-received signals for further processing based on the SNR detection [2]. The output SNRs of the M-SC receiver can be obtained as [16]

$$\gamma_{M-SC}=\frac{E_b}{N_0}Max\left(y_1^2,y_2^2,....,y_M^2\right) \tag{3}$$

The PDF of the output SNR of the r^{th} branch of the SC receiver can be obtained from (2) by performing the random variable transformation as per relation $\gamma_r=y_r^2\frac{E_b}{N_0}$ as

$$f_\gamma\left(\gamma_r\right)=\frac{2\mathrm{Z}^{\frac{(m+k)}{2}}}{\Gamma\left(m\right)\Gamma\left(k\right)}\gamma_r^{\frac{(m+k-2)}{2}}\mathrm{K}_{k-m}\left[2\sqrt{\mathrm{Z}\gamma_r}\right],\quad \gamma_r\geq 0 \tag{4}$$

where $\mathrm{Z}=\frac{km}{\bar{\gamma}}$.

From the relation (4) and by changing the limits using [18, (6.561.19)], the expression of the CDF can be given as

$$F_\gamma\left(\gamma_{th}\right)=\frac{4\sqrt{\pi}}{2^{m+k+p+\frac{1}{2}}\Gamma\left(m\right)\Gamma\left(k\right)}\sum_{p=0}^{k-m-\frac{1}{2}}\frac{\left(k-m-\frac{1}{2}+p\right)!}{p!\left(k-m-\frac{1}{2}-p\right)!}g\left(m+k-p-\frac{1}{2},2\sqrt{\Xi\gamma_{th}}\right) \tag{5}$$

Now, using the relation (5), the final CDF expression is given as

$$F_\gamma\left(\gamma_{th}\right)=\frac{4\sqrt{\pi}}{2^{m+k+p+\frac{1}{2}}\Gamma\left(m\right)\Gamma\left(k\right)}\sum_{p=0}^{k-m-\frac{1}{2}}\frac{\left(k-m-\frac{1}{2}+p\right)!\left(m+k-p-\frac{3}{2}\right)!}{p!\left(k-m-\frac{1}{2}-p\right)!}\left(1-\exp\left(-2\sqrt{\Xi\gamma_{th}}\right)\sum_{t=0}^{m+k-p-\frac{3}{2}}\frac{\left(2\sqrt{\Xi\gamma_{th}}\right)^t}{t!}\right) \tag{6}$$

The joint CDF of M branch input SNRs can be obtained using the multiplication of M branch CDFs given in (6) for independent input branch fading signals. Thus, the expression of the CDF for combiner output SNR is given by substituting $\gamma_{th}=\gamma_{M-SC}\forall r$ as

$$F_\gamma\left(\gamma_{M-SC}\right)=\sum_{\substack{p_i=0\\ i=1,2,\ldots M}}^{k-m-\frac{1}{2}}\frac{\pi^{\frac{M}{2}}\prod_{i=1}^{M}\left\{\left(k-m-\frac{1}{2}+p_i\right)!\left(m+k-p_i-\frac{3}{2}\right)!\right\}}{2^{Mm+Mk+\sum_{i=1}^{M}p_i-\frac{3M}{2}}\left\{\Gamma(m)\Gamma(k)\right\}^M\prod_{i=1}^{M}\left\{p_i!\left(k-m-\frac{1}{2}-p_i\right)!\right\}}$$
$$\times\left[1-\exp\left(-2\sqrt{\Xi\gamma_{M-SC}}\right)\sum_{t=0}^{m+k-p-\frac{3}{2}}\frac{\left(2\sqrt{\Xi\gamma_{M-SC}}\right)^t}{t!}\right]^M \quad (7)$$

The CDF expression of the SC receiver can be rewritten by applying the binomial theorem as

$$F_\gamma(\gamma_{M-SC})=\sum_{\substack{p_i=0\\ i=1,2,\ldots M}}^{k-m-\frac{1}{2}}\sum_{q=0}^{M}\sum_{\substack{t_n=0\\ n=1,2,\ldots q}}^{m+k-p-\frac{3}{2}}\frac{\pi^{\frac{M}{2}}(-1)^q\binom{M}{q}\left(2\sqrt{Z}\right)^{\sum_{n=1}^{q}t_n}}{2^{Mm+Mk+\sum_{i=1}^{M}p_i-\frac{3M}{2}}\prod_{n=1}^{q}t_n!\left\{\Gamma(m)\Gamma(k)\right\}^M}$$
$$\times\frac{\prod_{i=1}^{M}\left\{\left(k-m-\frac{1}{2}+p_i\right)!\left(m+k-p_i-\frac{3}{2}\right)!\right\}}{\prod_{i=1}^{M}\left\{p_i!\left(k-m-\frac{1}{2}-p_i\right)!\right\}}\gamma_{M-SC}^{\frac{\sum_{n=1}^{q}t_n}{2}}\exp\left(-2q\sqrt{Z\gamma_{M-SC}}\right) \quad (8)$$

The received RF signal is then inserted into a power splitter that is assumed to be perfect without noise. The output of the power splitter splits the signal power to the information decoding (ID) receiver denoted by (1-β) and that to the energy harvesting (EH) by β, where β varies from 0 to 1, and the value of β can be adjusted over different fading states. The signal split to the EH receiver harvested some energy, and to the ID receiver goes through a sequence of standard operations

Now, applying the random variable transformation, the expression of the CDF can be given as

$$F_s(s)=\sum_{\substack{p_i=0\\ i=1,2,\ldots M}}^{k-m-\frac{1}{2}}\sum_{q=0}^{M}\sum_{\substack{t_n=0\\ n=1,2,\ldots q}}^{m+k-p-\frac{3}{2}}\frac{\pi^{\frac{M}{2}}(-1)^q\binom{M}{q}\left(2\sqrt{Z}\right)^{\sum_{n=1}^{q}t_n}\beta^{-\left(\frac{\sum_{n=1}^{q}t_n+2}{2}\right)}}{2^{Mm+Mk+\sum_{i=1}^{M}p_i-\frac{3M}{2}}\prod_{n=1}^{q}t_n!\left\{\Gamma(m)\Gamma(k)\right\}^M}$$
$$\times\frac{\prod_{i=1}^{M}\left\{\left(k-m-\frac{1}{2}+p_i\right)!\left(m+k-p_i-\frac{3}{2}\right)!\right\}}{\prod_{i=1}^{M}\left\{p_i!\left(k-m-\frac{1}{2}-p_i\right)!\right\}}s^{\frac{\sum_{n=1}^{q}t_n}{2}}\exp\left(-2q\sqrt{\frac{Zs}{\beta}}\right) \quad (9)$$

The PDF can be obtained by differentiating (9) w.r.t. s. The final expression of the PDF of the M-SC receiver can be given as

$$f_s(s)=\sum_{\substack{p_i=0\\i=1,2,\ldots M}}^{k-m-\frac{1}{2}}\sum_{q=0}^{M}\sum_{\substack{t_n=0\\n=1,2,\ldots q}}^{m+k-p-\frac{3}{2}}\frac{\pi^{\frac{M}{2}}(-1)^q\binom{M}{q}\left(2\sqrt{Z}\right)^{\sum_{n=1}^{q}t_n}\beta^{-\left(\frac{\sum_{n=1}^{q}t_n}{2}\right)}}{2^{Mm+Mk+\sum_{i=1}^{M}p_i-\frac{3M}{2}+1}\prod_{n=1}^{q}t_n!\left\{\Gamma(m)\Gamma(k)\right\}^M}$$
$$\times\frac{\prod_{i=1}^{M}\left\{\left(k-m-\frac{1}{2}+p_i\right)!\left(m+k-p_i-\frac{3}{2}\right)!\right\}}{\prod_{i=1}^{M}\left\{p_i!\left(k-m-\frac{1}{2}-p_i\right)!\right\}}e^{-2q\sqrt{\frac{Zs}{\beta}}}\left[\sum_{n=1}^{q}t_n s^{\frac{\sum_{n=1}^{q}t_n}{2}-1}-2q\sqrt{\frac{Z}{\beta}}s^{\frac{\sum_{n=1}^{q}t_n-1}{2}}\right]\tag{10}$$

3. Performance Analysis of the M-SC Receiver Over K_G Fading Channel

3.1 Average Output SNR

The average output SNR $\bar{\gamma}_{out}$ of the M-SC receiver over K_G fading channels for the PS scheme is given as $\bar{\gamma}_{out}=\int_0^\infty sf_s(s)\,ds$. Substituting $f_s(s)$ from (10); the expression for $\bar{\gamma}_{out}$ can be obtained as

$$\bar{\gamma}_{out}=\frac{2\Xi^{\frac{(m+k)}{2}}}{(1-\beta)^{\frac{(m+k)}{2}}\Gamma(m)\Gamma(k)}\int_0^\infty s^{\frac{(m+k)}{2}}K_{k-m}\left[2\sqrt{\frac{\Xi s}{1-\beta}}\right]ds\tag{11}$$

By changing the limits and solving the integration using [18, (6.561.16)], the final expression for average SNR will results

$$\bar{\gamma}_{out}=\frac{\bar{\gamma}(1-\beta)}{km\Gamma(m)\Gamma(k)}\Gamma(k+1)\Gamma(m+1)\tag{12}$$

3.2 Average Bit Error Rate (Aber)

ABER is an important metric for measuring a diversity receiver's performance operating in a fading environment. The CDF expression in (9) can be used to determine the closed-form expression of ABER for the M-SC receiver. The ABER can be expressed using CDF of the output SNR taken from [19] is given as

$$\bar{P}_e=-\int_0^\infty P_e^{'}(s)F_s(s)\,ds\tag{13}$$

where $P_e^{'}(s)$ is the conditional error probability (CEP), which is given by [19]

$$P_e^{'}(s)=\frac{-\xi^{\eta}s^{\eta-1}e^{\frac{-\xi s}{\beta}}}{2\beta^{\eta-1}\Gamma(\eta)}\tag{14}$$

where ξ and η are constant, and their values depend on binary modulation used in the system. For different binary modulations the values are given as: (ξ , η) = (1, 0.5) for BPSK, (ξ , η) = (0.5, 0.5) for BFSK, (ξ , η) = (1, 1) for DBPSK , (ξ , η) = (0.5,1) for NCBFSK [4].

Plugging the value of $F_s(s)$ and $P_e^{'}(s)$ from (9) and (14) into (13), ABER can be given as

$$\bar{P}_e = \sum_{\substack{p_i=0\\ i=1,2,\dots M}}^{k-m-\frac{1}{2}} \sum_{q=0}^{M} \sum_{\substack{t_n=0\\ n=1,2,\dots q}}^{m+k-p-\frac{3}{2}} \frac{\xi^{\eta}\pi^{\frac{M}{2}}(-1)^q \binom{M}{q}\left(2\sqrt{Z}\right)^{\sum_{n=1}^{q} t_n}}{2^{Mm+Mk+\sum_{i=1}^{M} p_i-\frac{3M}{2}}\beta^{\eta-1}\Gamma(\eta)\prod_{n=1}^{q} t_n!}$$
$$\times \frac{\prod_{i=1}^{M}\left\{\left(k-m-\frac{1}{2}+p_i\right)!\left(m+k-p_i-\frac{3}{2}\right)!\right\}}{\prod_{i=1}^{M}\left\{p_i!\left(k-m-\frac{1}{2}-p_i\right)!\right\}} \frac{\beta^{-\left(\frac{\sum_{n=1}^{q} t_n+2}{2}\right)}}{\left\{\Gamma(m)\Gamma(k)\right\}^M} \tag{15}$$
$$\times\int_0^{\infty} s^{\sum_{n=1}^{q} t_n+2\eta-1} e^{\frac{-\xi s^2}{\beta}-2q\sqrt{\frac{Z}{\beta}}s}\,ds$$

Solving the above integral using [18, (3.462.1)], the final expression for ABER can be given as

$$\bar{P}_e = \sum_{\substack{p_i=0\\ i=1,2,\dots M}}^{k-m-\frac{1}{2}} \sum_{q=0}^{M} \sum_{\substack{t_n=0\\ n=1,2,\dots q}}^{m+k-p-\frac{3}{2}} \frac{\xi^{-\frac{\sum_{n=1}^{q} t_n}{2}}\pi^{\frac{M}{2}}(-1)^q}{2^{Mm+Mk+\sum_{i=1}^{M} p_i-\frac{3M}{2}-\frac{\sum_{n=1}^{q} t_n}{2}+\eta}} \frac{\binom{M}{q}\left(\sqrt{Z}\right)^{\sum_{n=1}^{q} t_n}\Gamma\left(\sum_{n=1}^{q} t_n+2\eta\right)}{\Gamma(\eta)\prod_{n=1}^{q} t_n!\left\{\Gamma(m)\Gamma(k)\right\}^M}$$
$$\times \frac{\prod_{i=1}^{M}\left\{\left(k-m-\frac{1}{2}+p_i\right)!\left(m+k-p_i-\frac{3}{2}\right)!\right\}}{\prod_{i=1}^{M}\left\{p_i!\left(k-m-\frac{1}{2}-p_i\right)!\right\}} \exp\left(\frac{q^2 Z}{2\xi}\right) D_{-\sum_{n=1}^{q} t_n+2\eta}\left(q\sqrt{\frac{2Z}{\xi}}\right) \tag{16}$$

where, $D_{\nu}(z)$ is the parabolic cylindrical function [18].

4. Numerical Results and Discussion

In this section, we present the performance of the SC receiver for the K_G fading environment. The numerical results have been performed, and the proposed analysis is validated through the Monte-Carlo simulation. The obtained results are plotted for different fading parameters, i.e., k and m and power splitter factor β that are selected suitably to present the complete analysis of the system. Here, we introduce the ABER and the plot of harvested power vs. SNR in dB. It can be easily identified that all the performance measures degrade considerably with simultaneous information and energy transmission.

Fig. 2 and Fig. 3 plot the ABER vs. average SNR for different values of k and m along with the variation in β considering the number of diversity antenna as M=2 and M=5 in both coherent BPSK and BFSK modulation schemes. From the plot, it can be analyzed that the performance is seen to degrade with the increased value of k, m, and β. When m=1, k=1.5, and β=0.4, we get the worst-case scenario and best performance when m=4, k=4.5, and β=0.8. As the number of diversity branches increases, i.e., M=2 to M=5, an improvement in the receiver performance is observed in the figure. These results because an increase in diversity gain improves the communication channel and reduces the effect of deep fading. Further, we observe that BPSK performs better than BFSK due to the separation of signal points in the constellation diagram, and their performance improves with improving system parameters (k, m, and β). Here, the performances are weak in the high shadowing effect due to insufficient signaling, which shows by the reduced value of k and m.

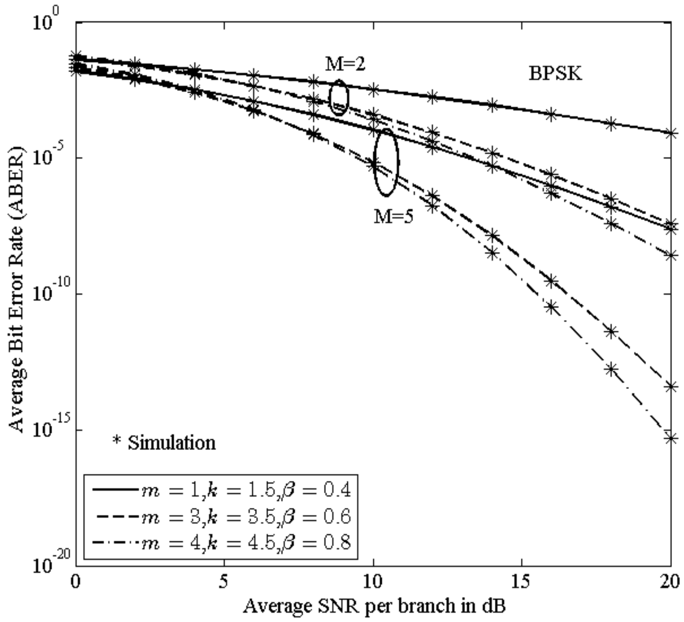

Fig. 2 - ABER for BPSK

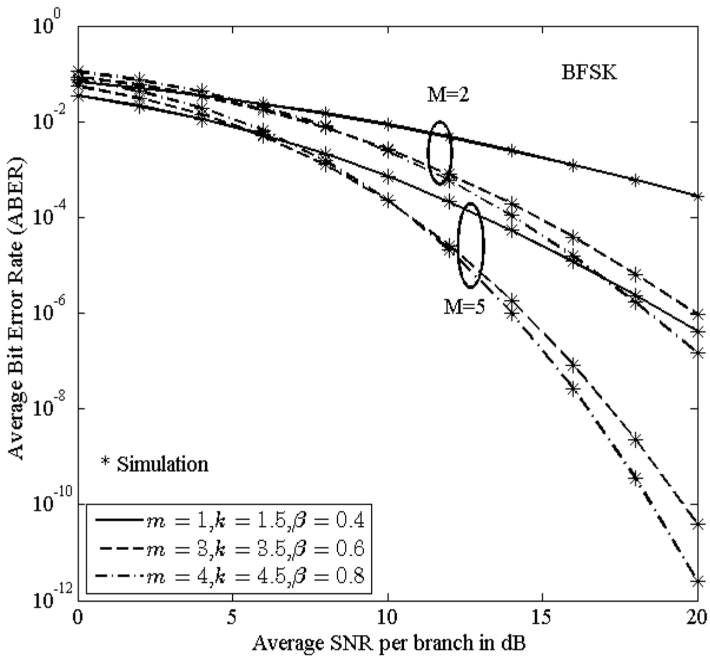

Fig. 3 - ABER for BFSK

In Fig. 4 and 5, ABER vs. average SNR is plotted for non-coherent modulation schemes. The behaviour is similar, except coherent performs better than the non-coherent modulation for a similar environment. These results due to the fact that the probability of error increases in the case of non-coherent modulation, in contrast to the coherent modulation. The numerical results are compared with the Monte-Carlo simulation denoted by asterisk markers. It is clear from the figure that the analytical work perfectly matches the simulation result over the entire SNR region.

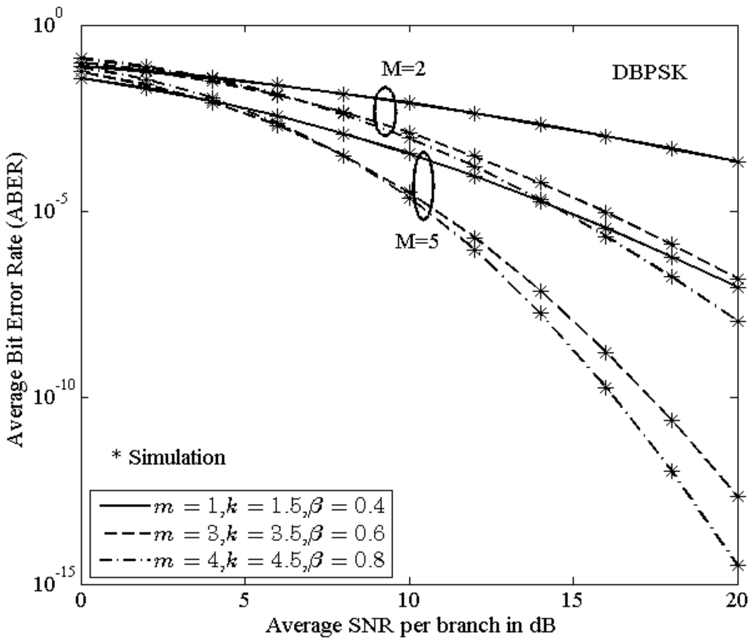

Fig. 4 - ABER for DBPSK

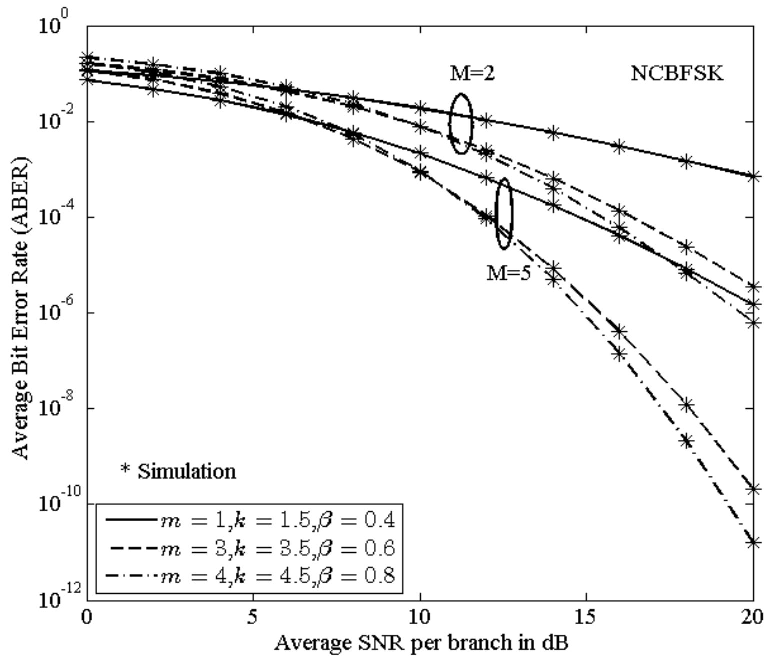

Fig. 5 - ABER for NCBFSK

Now, from the power vs. SNR curve considering M=2, m=4, k=4.5, and β=0.4 is shown in Fig. 6. It can be observed that a significant amount of energy can be harvested at the receiver above 40 dB SNR, beyond which the harvested power is increased exponentially. The transmitter is always supposed to connect with a conventional power source, so maintaining a high SNR is possible.

From Fig. 2, Fig. 3, Fig. 4, and Fig. 5, as the number of diversity branches M increases, the ABER performance is improved, clearly visible from the figure. With the rise in redundant paths, the probability of deep fading reduces. However, the improvement is not significant from the energy harvesting point of view. In this case, the receiver has no fixed power supplies, and thus we get the expected power, i.e., 0.025 nWatt, as shown in Fig. 6.

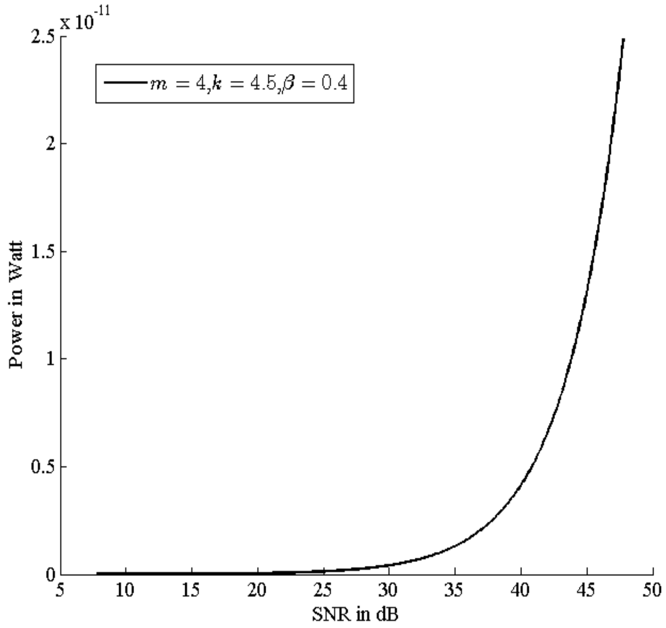

Fig. 6 – Power vs. SNR in dB

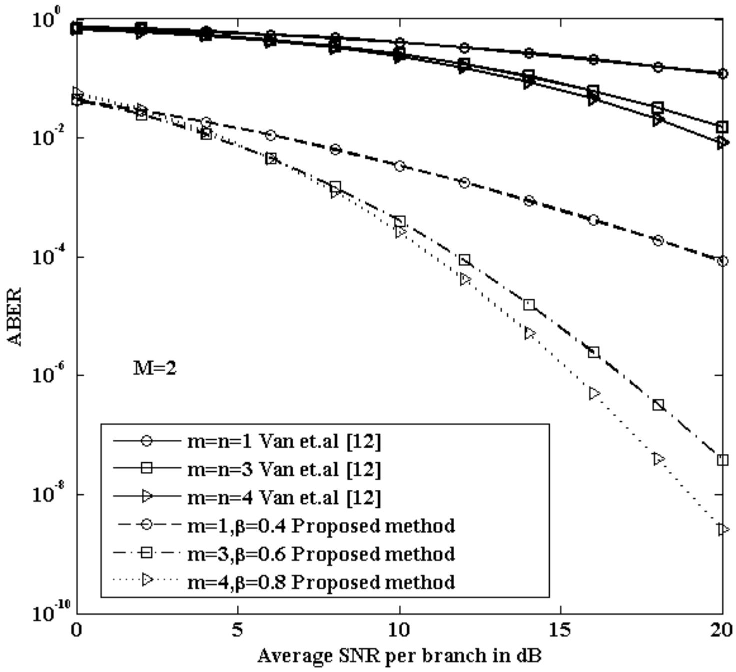

Fig. 7 – Comparison of ABER vs average SNR between the proposed system over K_G fading channel and that given in Van et.al [12] for Nakagami fading channel

Fig. 7 shows the comparison of ABER vs. average SNR between the proposed method for K_G fading channel and that reported in [12] for Nakagami fading channel. We have compared (16) of the proposed method with [12, (14)], by keeping diversity antennas M=2 and varying β of the proposed method and fading parameter m. It is clear from the plot that the ABER curve decreases with increase in β and m. As the value of m and β increases, the proposed curves significantly improves, which is clearly visible from the separation of the graphs. Thus, our results perform better than that reported in [12] for high value of SNR.

5. Conclusion

The closed-form expression of the PDF and the CDF of the output SNR for the M-SC receiver over K_G fading channels, along with the power splitter factor (β), have been presented in this work. The receiver performance has been analyzed through the average SNR and ABER. We have shown that the system's performance improves for a high value of shaping parameters and power splitter factor. The derived expressions are in the form of Gamma function and parabolic cylindrical function, making the computation easier. Numerically evaluated results have been plotted to demonstrate the effect of fading parameter, the number of diversity antennas, and the power splitter factor on the receiver. The obtained results were verified with the help of Monte-Carlo simulations.

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